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RECENT PUBLICATIONS

Scientific Paper No. 31 The three-dimensional analysis of meteorological data.

By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

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A full description is given of the 10-level numerical weather prediction model which has been developed by the Meteorological Office during the past few years for use in investigating the dynamics of fronts and in predicting rainfall. The formulation includes representation of the effects of surface friction, topography, surface exchanges of sensible and latent heat, sub-grid-scale convection, and lateral diffusion. An example of a recently computed forecast is included.

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SUBSTANTIAL SNOWFALLS OVER THE UNITED KINGDOM, 1954–69

By C. A. S. LOWNDES

Summary. Data are given on the frequency of substantial snowfalls (7 mm or more of precipitation in 24 hours) during the period 1954–69 at 41 stations in the United Kingdom. Frequencies are given for each month and year, for each day of the month, and also for occasions when subsequently there was a complete snow cover for periods of at least 24 hours, 3 days, 5 days, 10 days and 20 days. Maps are given to show the corresponding geographical distributions.

The frequency of substantial snowfall is given for various synoptic situations and a description is given of the situation during persistent snow cover in the period December 1962 to February 1963.

Introduction. For this investigation, a substantial snowfall was defined as at least 7 mm of precipitation falling as snow or sleet,* sometimes with hail, during 24-hour periods beginning at 09 GMT and 21 GMT. This represents in general a snow depth of about 8 cm.[1] A study was made of all such occasions which occurred at the 41 reporting stations in the *Daily Weather Report*,† shown in Figure 1, for the 15 'winter seasons' 1954–55 to 1968–69, the 'winter season' being defined as the 8 months October to May. Of the 41 stations, 8 did not report for the whole period and nearby stations were also used. The 8 stations and their substitutes with the heights of the stations above mean sea level in metres were as follows :

Thorney Island (4 m)/Tangmere (16 m) up to 1957/58
Wattisham (89 m)/Felixstowe (3 m) up to 1960/61
St Mawgan (103 m)/St Eval (103 m) up to 1957/58
Finningley (10 m)/Lindholme (5 m) up to 1957/58
Kilnsea (12 m)/Spurn Head (9 m) up to 1964/65
Leeming (32 m)/Dishforth (32 m) up to 1964/65
Carlisle (26 m)/Silloth (8 m) up to 1960/61
Abbotsinch (5 m)/Renfrew (8 m) up to 1955/56

The difference in height between the station and its substitute is 5 m or less for five of the stations and the substitute snowfall values are probably reasonably representative of the station. At the other three stations,

* Sleet is here defined as snow and rain (or drizzle) together or snow melting as it falls.
† London, Meteorological Office. *Daily Weather Report.*

FIGURE 1—POSITIONS OF STATIONS USED

Figures show height above MSL in metres

Wattisham, Carlisle and Thorney Island, the difference in height is 86 m, 18 m, and 12 m respectively, and the substitute snowfall values should be treated with due caution.

The frequency of substantial snowfalls. Table I shows the total number of occasions for each month when there was substantial snowfall. All occasions for each of the 41 stations are included.

TABLE I—NUMBER OF OCCASIONS* WITH SUBSTANTIAL SNOWFALL FOR THE MONTHS OCTOBER TO MAY 1954–69

Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total
1	34	110	142	164	88	22	1	562

* All occasions for each of the 41 stations are included. For example, if 5 stations had a substantial snowfall during a particular 24 hours, then this was counted as 5 occurrences. (Contrast Table III p. 196.)

Of the total number of occasions, about 30 per cent occurred in February and 25 per cent in January. A further 20 per cent occurred in December and about 15 per cent in March. Roughly 5 per cent occurred in each of the months November and April. There was only one occasion in October and one in May, i.e. on 17 October 1967 and 14 May 1955. On both occasions the station concerned was Dyce and the snow and sleet were associated with a polar low in a northerly airstream. However, the snow cover dispersed in less than 24 hours on each occasion. Of the total number of occasions, 36 (6 per cent) were associated with 20 mm or more in 24 hours; of the 36, slightly less than half occurred at stations in Scotland. On 7 occasions, the precipitation totalled 30 to 39 mm in 24 hours.

Figure 2 shows the frequency of occurrence of substantial snowfalls over the United Kingdom for each day of the months November to April. If one or more stations had a substantial snowfall on a particular day, then this was counted as one qualifying day. The number of days with substantial snowfall averaged about 1 for the second half of November and increased to an average of about 2 for the first 10 days of December. After the 10th there was a decline until Christmas after which the number of days averaged about 3 until the end of the month. The number of days averaged about 2 for January and 2–3 for February. For 18 January and 19 and 20 February there was substantial snowfall in five of the 15 years. There was a decline towards the end of February to an average of 1–2 days which continued to 24 March. From 25 March to the end of April only the first three days of April had more than one occurrence of substantial snowfall.

Table II shows the number of occasions of substantial snowfall when subsequently there was a complete snow cover which lasted for at least (i) 24 hours, (ii) 3 days, (iii) 5 days, (iv) 10 days and (v) 20 days. All such occasions for each of the 41 stations are included. Of the total number of occasions with substantial snowfall (562) only 57 per cent resulted in a complete snow cover which persisted for at least 24 hours. There were no such occasions in October and May, and only one in April. On 30 per cent of occasions the snow cover persisted for 3 days or more and on 17 per cent of occasions for 5 days or more. There were no such occasions in October, April and May. The 6 per cent of occasions when the snow cover persisted for 10 days or more occurred in the four months November to February and the 15 occasions when the snow cover persisted for 20 days or more occurred in the three months December, January and February.

TABLE II—NUMBER OF OCCASIONS* WITH SUBSTANTIAL SNOWFALL FOR THE MONTHS OCTOBER TO MAY 1954–69 WHEN SUBSEQUENTLY THERE WAS A COMPLETE SNOW COVER FOR VARIOUS PERIODS

Snow cover persisted for at least	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total
(i) 24 hours	0	12	74	106	100	30	1	0	323
(ii) 3 days	0	9	44	60	49	9	0	0	171
(iii) 5 days	0	7	22	35	30	2	0	0	96
(iv) 10 days	0	2	7	13	10	0	0	0	32
(v) 20 days	0	0	5	5	5	0	0	0	15

* All such occasions for each of the 41 stations are included. For example, if 5 stations had a substantial snowfall during a particular 24 hours when subsequently there was a complete snow cover for at least 3 days, then this was counted as 5 occurrences of type (ii).

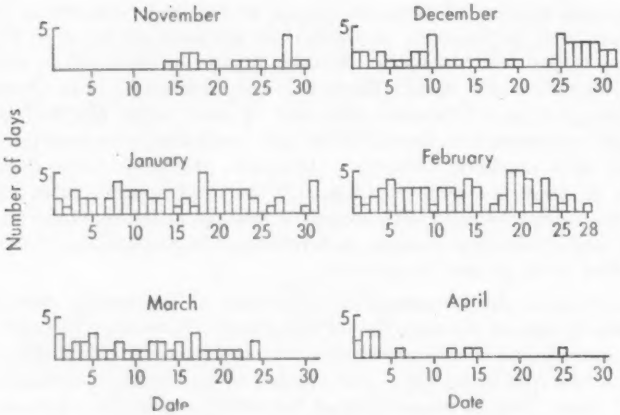


FIGURE 2—FREQUENCY OF OCCURRENCE* OF SUBSTANTIAL SNOWFALL FOR EACH DAY OF THE MONTHS NOVEMBER TO APRIL OVER 15 YEARS 1954–69

* If one or more stations had a substantial snowfall on a particular day, then this was counted as one qualifying day. See also Table III.

Table III shows the number of days with substantial snowfall over the United Kingdom for each month of the 15 winter seasons, i.e. if one or more stations had a substantial snowfall on a particular day, then this was counted as one qualifying day. Considering only the months November to April, the number of days has increased since 1961 for all months except January. The increases in the months November, December and April are large enough to suggest that they might be significant. Similar increases were noted by Clarke[2] for November, December, March and April in a study of snowfalls of any intensity over south-east England for the same 15-year period. There was no substantial snowfall in January and February in only one or two of the 15

TABLE III—NUMBER OF DAYS* WITH SUBSTANTIAL SNOWFALL OVER THE UNITED KINGDOM FOR EACH MONTH OF THE 15 WINTER SEASONS 1954–69

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total
1954–55	0	0	0	10	11	5	0	1	27
1955–56	0	0	3	9	7	0	0	0	19
1956–57	0	1	3	2	3	0	0	0	9
1957–58	0	0	1	7	9	9	2	0	28
1958–59	0	0	1	9	0	0	0	0	10
1959–60	0	0	0	6	1	0	0	0	7
1960–61	0	0	0	1	1	0	1	0	3
1961–62	0	1	8	1	1	4	1	0	16
1962–63	0	5	8	7	6	0	1	0	27
1963–64	0	1	0	0	2	3	0	0	6
1964–65	0	1	6	4	2	5	0	0	18
1965–66	0	8	3	2	5	1	4	0	23
1966–67	0	2	3	0	2	2	0	0	9
1967–68	1	0	4	4	4	1	4	0	18
1968–69	0	0	5	4	14	5	0	0	28
Total	1	19	45	66	68	35	13	1	248

* If one or more stations had a substantial snowfall on a particular day, then this was counted as one qualifying day.

winters but in November and April there was no substantial snowfall in 8 or 9 of the 15 winters. There was only one substantial snowfall in October and one in May.

Table IV shows the synoptic situations associated with substantial snowfalls for each month. All occasions for each of the 41 stations are included. Some 51 per cent of occasions were associated with warm fronts or warm occlusions, the majority of which moved from (or were situated to) the south, south-west or west of the station. Many of these fronts, in particular those to the south of the station, approached the station but did not reach it, becoming quasi-stationary before dispersing or retrogressing. This effect was often the result of small waves or wave depressions moving in an easterly direction along the front. Clarke[2] found that 75 per cent of warm fronts from the south which gave snow over south-east England did not reach the area. A further 32 per cent of occasions with substantial snowfall were associated with polar lows or troughs in northerly airstreams. Relatively few of these occasions were in November and April and only one in both October and May. Polar lows or troughs which moved westwards in easterly airstreams accounted for 6 per cent of occasions. There were no such occasions in October, November, April and May, and only one in December during the 15 years. A further 6 per cent were associated with showers, mainly in northerly and easterly airstreams; 3 per cent with cold fronts or cold occlusions mainly from the north or east; one per cent with wave depressions moving from the west or north-west over or in the vicinity of the station and one per cent with troughs

TABLE IV—SYNOPTIC SITUATIONS ASSOCIATED WITH OCCASIONS* OF SUBSTANTIAL SNOWFALL

Synoptic situation		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total	
Polar lows or troughs in northerlies		1	12	39	43	52	24	8	1	180	
Polar lows or troughs in easterlies		0	0	1	11	14	7	0	0	33	
Warm fronts or warm occlusions (direction of approach)	S	0	3	32	43	51	9	4	0	142	288
	SW	0	8	1	3	14	12	5	0	43	
	W	0	4	20	21	14	13	3	0	75	
	NW	0	1	4	0	3	10	0	0	18	
	N	0	0	2	0	6	1	0	0	9	
	E	0	1	0	0	0	0	0	0	1	
Cold fronts or cold occlusions (direction of approach)	N	0	0	1	5	1	2	0	0	9	15
	E	0	0	2	2	1	0	0	0	5	
	S	0	0	0	1	0	0	0	0	1	
Wave-depressions (direction of approach)	W	0	0	2	0	0	0	0	0	2	8
	NW	0	0	0	2	0	4	0	0	6	
Showers (surface geostrophic wind direction)	N	0	3	4	5	1	0	0	0	13	32
	NE	0	0	0	0	0	4	0	0	4	
	E	0	1	0	2	4	0	0	0	7	
	SE	0	0	1	1	2	0	0	0	4	
	W	0	0	0	0	0	0	1	0	1	
	NW	0	1	0	0	1	1	0	0	3	
Troughs in westerlies		0	0	1	2	0	1	1	0	5	
Complex depression		0	0	0	1	0	0	0	0	1	
Total		1	34	110	142	164	88	22	1	562	

* All occasions for each of the 41 stations are included. For example, if 5 stations had a substantial snowfall during a particular 24 hours then this was counted as 5 occurrences.

in westerlies, often to the rear of a cold front. One occasion was associated with a small depression moving within a large, slow-moving complex depression.

Geographical distribution of substantial snowfalls. Figure 3 shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations. As might be expected, the highest number (52) occurred at Eskdalemuir which at a height of 239 m is to some extent representative of the high ground in Scotland. The snowfalls at Eskdalemuir were mainly associated with warm fronts or warm occlusions which moved from (or were situated to) the south or west and relatively few with polar lows or troughs.

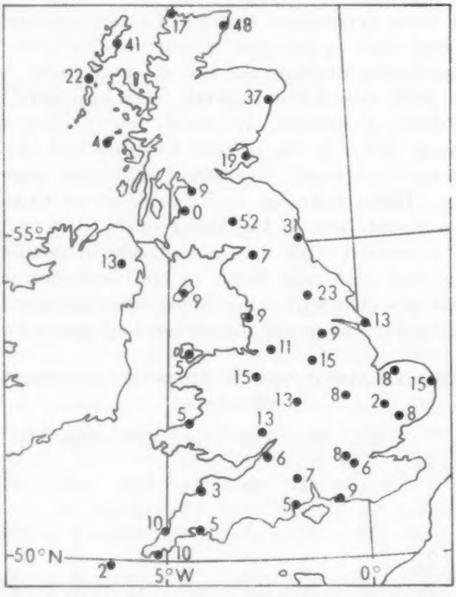


FIGURE 3—NUMBER OF OCCASIONS OF SUBSTANTIAL SNOWFALL DURING THE 15 WINTERS AT EACH OF THE 41 STATIONS

The second highest number of occasions (48) occurred at Wick (36 m) and the third highest (41) at Stornoway (3 m), the snowfall at both stations being mainly caused by polar lows or troughs in northerly airstreams. It is interesting to note that at Cape Wrath (105 m), situated on the north coast of Scotland in much the same latitude as Wick and Stornoway, there were only 17 occasions, also mainly associated with polar lows or troughs in northerlies. It is probable that the low number of occasions at Cape Wrath is associated with a relatively over-exposed rain-gauge situated at a height of 105 metres, within the lighthouse enclosure, near the edge of a sheer cliff facing northwards.

The fourth highest number of occasions (37) occurred at Aberdeen/Dyce (59 m) on the east coast of Scotland and the fifth highest (31) at Tynemouth (29 m) on the east coast of northern England. The snowfalls at Dyce were mainly associated with polar lows or troughs in northerlies and with warm fronts or warm occlusions which moved from (or were situated to) the south

or west. At Tynemouth they were mainly associated with warm fronts or warm occlusions which moved from (or were situated in) the south-west quarter and with polar lows or troughs in northerlies and easterlies. At Leuchars (11 m) on the east coast of Scotland about halfway between Dyce and Tynemouth there were relatively few occasions (19), probably because of the shelter afforded by high ground to the north and south and to the relatively low altitude of the station. The occasions at Leuchars were mainly associated with the same synoptic types which brought the snowfalls to Tynemouth.

The lowest number of occasions (0) occurred, not as might be expected at Scilly/St Mary's, but at Prestwick Airport (10 m) on the west coast of southern Scotland. Prestwick is sheltered by high ground to the north, east and south, is adjacent to the relatively warm sea and is at a low altitude. It is interesting to note that the 9 occasions at nearby Abbotsinch (now Glasgow Airport) (5 m) were mostly associated with warm fronts or warm occlusions from the west or south-west which brought snow to Abbotsinch but which tended to bring rain rather than snow to Prestwick. None of the 9 occasions were associated with polar lows or troughs.

The second lowest number of occasions (2) occurred at Mildenhall (5 m) and Scilly (48 m). At Mildenhall, both occasions were associated with a warm occlusion situated to the south of the station. Other stations in East Anglia such as West Raynham (76 m), Gorleston (2 m) and Wattisham (89 m) had 18, 15 and 8 occasions respectively. Most of these occasions were associated with polar lows or troughs in northerly or easterly airstreams which presumably brought substantial snowfalls only to coastal areas of East Anglia. This supposition is supported by the fact that the 8 occasions of substantial snowfall at Wittering (66 m), which is situated to the west of East Anglia, were mainly associated with warm fronts or warm occlusions which moved from (or were situated to) the south and on only one occasion with a polar low or trough; also the 6 to 8 occasions at Kew (5 m) and London/Heathrow Airport (25 m), which are situated to the south of East Anglia, were nearly all associated with warm fronts or warm occlusions which moved from (or were situated to) the south and none with a polar low or trough. At Scilly, both occasions were associated with a polar low or trough in a northerly airstream but as might be expected on an island surrounded by a relatively warm sea, the snow cover lasted for less than 24 hours.

The fourth lowest number of occasions (3) occurred at Chivenor (6 m) in south-west England. Two occasions were associated with warm fronts and one with a polar low or trough in a northerly airstream but the snow cover lasted for less than 24 hours on two of the three occasions.

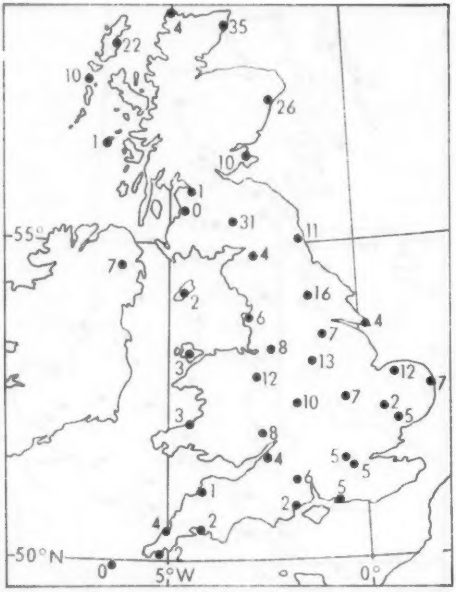
The fifth lowest number of occasions (4) occurred at Tiree (10 m) which is situated to the west of Scotland. It is interesting to note that whereas the 41 occasions at Stornoway and the 22 occasions at Benbecula were mainly associated with polar lows or troughs in northerlies, all of the 4 occasions at Tiree were associated with warm fronts or occlusions and none with polar lows or troughs. It has been noted above that neither Abbotsinch nor Prestwick had substantial falls associated with polar lows or troughs. However, 5 of the 13 occasions at Belfast/Aldergrove Airport (66 m) to the south of Tiree were caused by polar lows or troughs in northerlies.

For the 30 occasions when substantial snowfalls occurred at Stornoway in association with a northerly airstream, usually with a polar low or trough embedded in it, the average surface temperatures at Stornoway, Tiree and Aldergrove were 0°C, 1·5°C and 0·5°C respectively. There is a suggestion that coastal regions of western Scotland as far north as Tiree were free from substantial snowfalls associated with polar lows or troughs.

Figure 4*(a)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 24 hours. The number of occasions at each station, with the exception of Prestwick and Mildenhall, is lower than the corresponding number shown in Figure 3 and on average lower by 43 per cent. The snow cover lasted for less than 24 hours on about 70 per cent of all occasions associated with warm fronts or warm occlusions which moved from the south-west or west, often when the front moved through the station rather than becoming slow moving before reaching it. For other synoptic types the corresponding figures were: polar low or trough in northerly, 40 per cent; warm front from south, 30 per cent; polar low or trough in easterly, 20 per cent. In general, the number of occasions was 4 or less in the western coastal regions of Great Britain as far north as Tiree, including Anglesey and the Isle of Man, and in the south coastal regions of England. The numbers, in general, ranged from 5 to 13 for inland districts of England and Northern Ireland and for the eastern coastal districts of Great Britain as far north as Leuchars. For coastal districts of northern Scotland the numbers, in general, ranged from 10 to 35. The number of occasions at Eskdalemuir, to some extent representative of the high ground in Scotland, was 31. On the other hand there were only two occasions at Mildenhall in central East Anglia.

Figure 4*(b)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 3 days, a situation likely to cause considerable inconvenience. In general, the number of occasions was two or less in the western coastal districts of Great Britain as far north as Tiree, including Anglesey and the Isle of Man, and in the south coastal regions of England. The numbers, in general, ranged from 3 to 9 for inland districts of England and Northern Ireland and from 1 to 7 for the eastern coastal districts of Great Britain as far north as Leuchars. For coastal districts of Northern Scotland the numbers, in general, ranged from 5 to 19. The number of occasions at Eskdalemuir was 20. There were no occasions at Scilly, Plymouth/Mount Batten and Chivenor in south-west England; at Ronaldsway Airport in the Isle of Man; at Prestwick and Abbotsinch in Scotland.

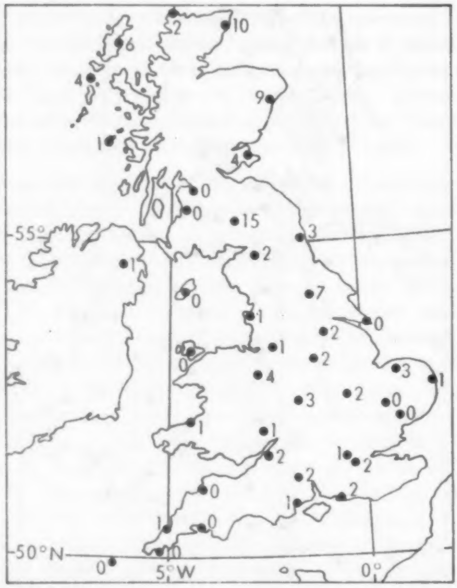
Figure 4*(c)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 5 days. There were no occasions at Scilly, Culdrose, Mount Batten and Chivenor in south-west England; at Mildenhall and Wattisham in East Anglia; at Kilnsea (Spurn Head); at Valley (Anglesey) and Ronaldsway (Isle of Man); at Prestwick and Abbotsinch in Scotland. There were 15 occasions at Eskdalemuir and for the coastal districts of northern Scotland the numbers, in general, ranged from 4 to 10. In England the highest numbers were 7 at Leeming, 4 at Shawbury and 3 at Tynemouth, Elmdon (now Birmingham Airport) and West Raynham.



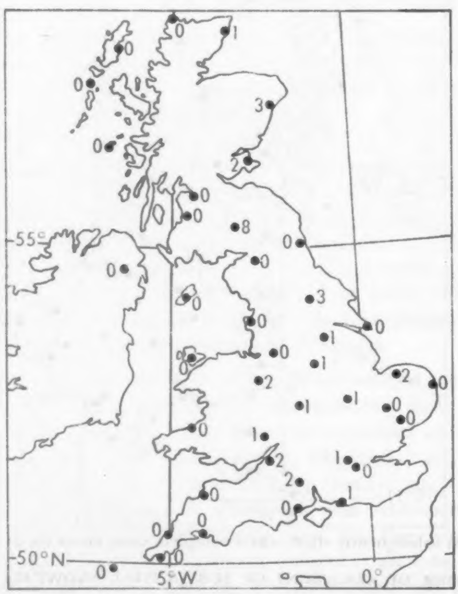
(a) When subsequently there was a complete snow cover for at least 24 hours

(b) When subsequently there was a complete snow cover for at least 3 days

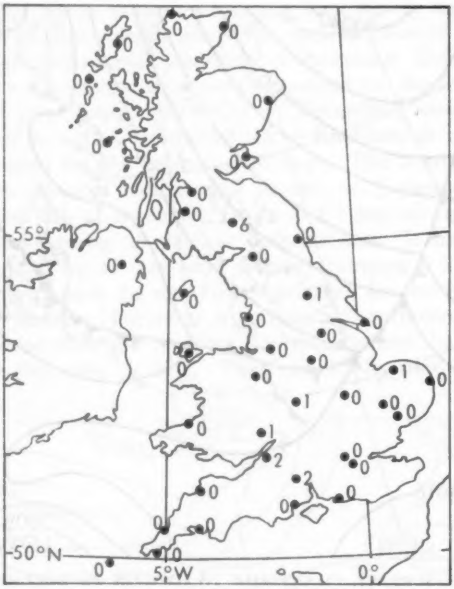
FIGURE 4—NUMBER OF OCCASIONS OF SUBSTANTIAL SNOWFALL DURING THE 15 WINTERS AT EACH OF THE 41 STATIONS



(c) When subsequently there was a complete snow cover for at least 5 days



(d) When subsequently there was a complete snow cover for at least 10 days



(e) When subsequently there was a complete snow cover for at least 20 days

FIGURE 4—*continued*

Figure 4*(d)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 10 days. There were 8 occasions at Eskdalemuir and for the eastern coastal districts of Scotland the numbers ranged from 1 to 3. In England the highest numbers were 3 at Leeming and 2 at Shawbury, West Raynham, Bristol/Filton and Boscombe Down. There was one occasion at Finningley, Watnall, Elmdon, Wittering, Ross-on-Wye, Heathrow and Thorney Island.

Figure 4*(e)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 20 days. There were 6 occasions at Eskdalemuir, 2 occasions at Filton and Boscombe Down and one at Ross-on-Wye, Elmdon, West Raynham and Leeming. All of the occasions at the English stations and 4 of the occasions at Eskdalemuir occurred during the months December 1962 to February 1963.

Occasions when the snow cover persisted for 20 days or more during the period December 1962 to February 1963. Figure 5 shows the surface chart for 18 GMT on 26 December 1962. At this time, a warm occlusion which was moving slowly southwards over central England marked the boundary between a cold northerly airstream and an even colder air mass over the Continent. It brought a substantial fall to Elmdon where a complete snow cover persisted for the following 32 days. The front continued to move southwards and reached the Channel region by 00 GMT on 27 December,

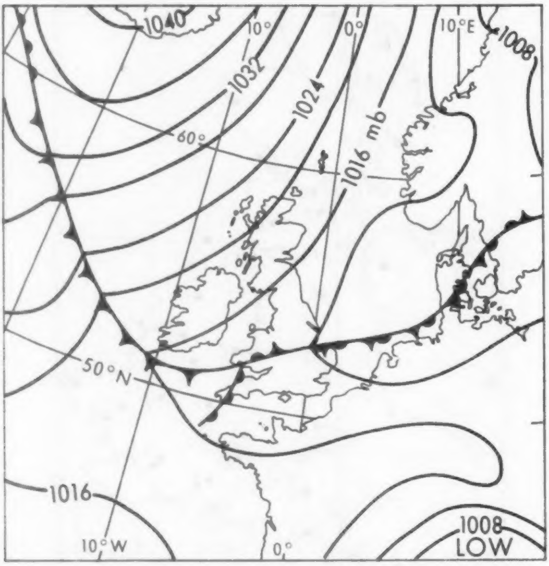


FIGURE 5—SURFACE CHART FOR 18 GMT ON 26 DECEMBER 1962

becoming quasi-stationary until losing its identity by 12 GMT on 29 December. By 18 GMT on 30 December (Figure 6) a wave depression had moved northwards from Biscay to a position south of Ireland having become partially

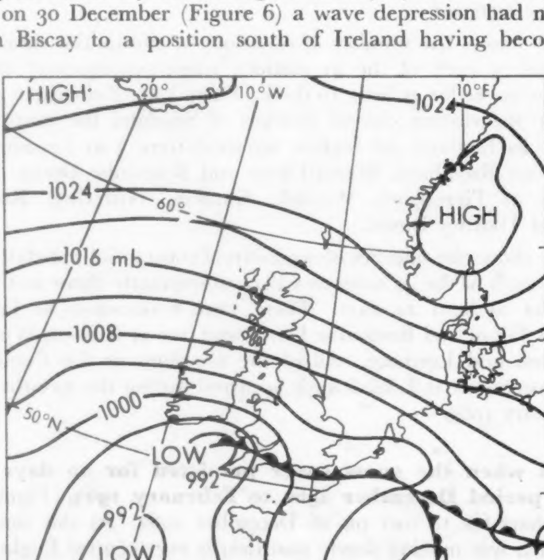


FIGURE 6—SURFACE CHART FOR 18 GMT ON 30 DECEMBER 1962

occluded with the warm occlusion moving very slowly northwards in the Channel region. A cold easterly airstream covered most of the British Isles. The front brought substantial snowfalls to Boscombe Down, Ross-on-Wye and Filton where a complete snow cover persisted for the following 30 days, 41 days and 32 days respectively. On 31 December, showers in a strong easterly airstream brought a substantal fall to Eskdalemuir where a complete snow cover persisted for the following 26 days. The front remained quasi-stationary in the Channel region until 12 GMT on 3 January 1963 causing further substantial falls at Boscombe Down and Filton where the snow cover persisted for the following 28 days at both stations. It moved northwards to northern England by 00 GMT on 4 January bringing a further substantial fall to Eskdalemuir where the snow cover persisted for the following 22 days. By 18 GMT on 4 January (Figure 7) it had moved southwards to East Anglia bringing substantial snowfalls to West Raynham where the snow cover also persisted for the following 22 days. The remarkable persistence of the snow

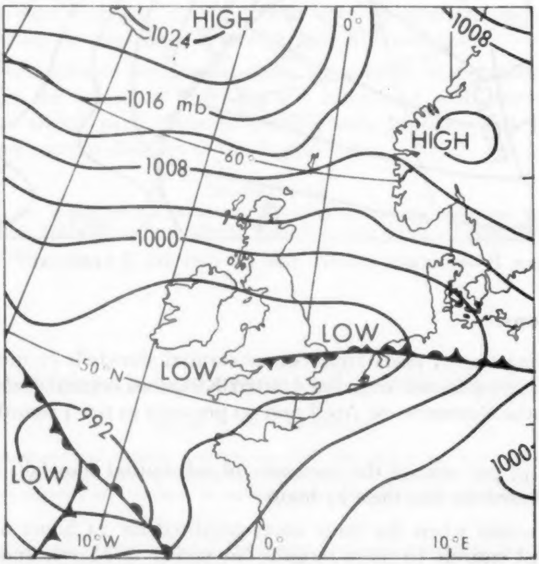


FIGURE 7—SURFACE CHART FOR 18 GMT ON 4 JANUARY 1963

cover throughout January 1963 was due to the cold easterly or anticyclonic types which predominated over the British Isles. On 31 January a cold front from the east brought a further substantial snowfall to Eskdalemuir where the snow cover persisted for the following 32 days. By 6 February, a deep depression was slow moving to the west of the British Isles and two warm occlusions moved northwards across the British Isles during the 6th to the 8th bringing substantial snowfalls to Leeming and Eskdalemuir where the snow cover persisted for the following 22 days and 25 days respectively. Figure 8 shows the surface chart for 00 GMT on 8 February when the second warm occlusion was moving northwards over England. The persistence of the

snow cover throughout February was associated with the cold south-easterly or anticyclonic types which predominated in particular over eastern districts of the British Isles.

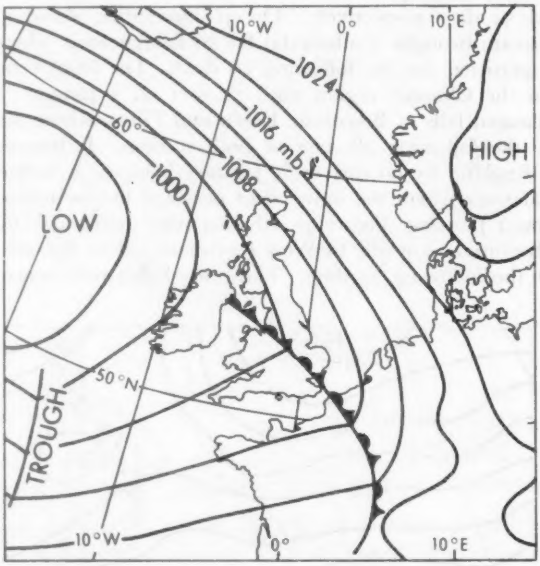


FIGURE 8—SURFACE CHART FOR 00 GMT ON 8 FEBRUARY 1963

Conclusions.

(i) During the 15 years 1954–69, substantial snowfalls (7 mm or more of precipitation in 24 hours) over the United Kingdom occurred almost entirely in the 6 months November to April and 90 per cent in the 4 months December to March.

(ii) On 43 per cent of the occasions of substantial snowfall, the resulting snow cover lasted for less than 24 hours.

(iii) Occasions when the snow cover persisted for 24 hours or more were limited almost entirely to the 5 months November to March and 86 per cent occurred in the 3 months December, January and February.

(iv) Occasions when the snow cover persisted for 3 days or more occurred in the 5 months November to March and 89 per cent in the 3 months December, January and February.

(v) There is a suggestion of a significant increase in substantial snowfalls in the months November, December and April from 1961 onwards.

(vi) There were substantial snowfalls in nearly all Januarys and Februarys but in only about half the Novembers and Aprils.

(vii) Half the substantial snowfalls were associated with warm fronts or warm occlusions which moved from (or were situated to) the south, south-west or west and a third with polar lows or troughs in northerly airstreams.

(viii) Polar lows or troughs in northerly or easterly airstreams brought a number of substantial falls to coastal stations of East Anglia but none to Mildenhall in central East Anglia.

(ix) There is a suggestion that coastal regions of western Scotland as far north as Tiree were free from substantial snowfalls associated with polar lows or troughs.

(x) On occasions of substantial snowfall when subsequently the snow cover persisted for at least 24 hours (Figure 4*(a)*) the highest frequency of occasions occurred at Eskdalemuir and in the eastern coastal districts of northern Scotland. The lowest frequencies occurred at Scilly, in the coastal districts of south-west England, in the west coast districts of Wales, northern England and Scotland as far north as Tiree, and at Mildenhall in East Anglia. There were no occasions at Scilly and Prestwick.

(xi) On occasions of substantial snowfall when subsequently the snow cover persisted for 3 days or more (Figure 4*(b)*) the distribution of frequencies was similar to that described in (x). There were no occasions at Scilly, Mount Batten, Chivenor, Ronaldsway, Prestwick and Abbotsinch.

(xii) The remarkable persistence of the snow cover at a number of stations in England in the winter of 1962–63 was associated with easterly or anti-cyclonic types which predominated during both January and February, in particular over eastern districts of the British Isles.

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2. CLARKE, P. C.; Snowfalls over south-east England, 1954–1969. *Weather, London,* **24**, 1969, pp. 438–447.

551.508.54

A RECORDER FOR RECORDING RUN-OF-WIND

By G. E. W. HARTLEY

Summary. Constructional details and photographs are given for a run-of-wind recorder. Easily variable gearing changes which facilitate range adjustments and the incorporation of the maximum number of standard or readily available parts are features that may be of special interest.

In March 1969 the Operational Instrumentation Branch of the Meteorological Office was asked to construct six recorders to be used with contact anemometers to record the run-of-wind in statute miles. Such an instrument made at Rothamsted Experimental Station, Hertfordshire, was available as a specimen.

The action of the recorder is as follows : the electrical impulses received from the anemometer energize the coil of a solenoid which, by means of a ratchet lever, turns a toothed wheel; the toothed-wheel spindle carries a worm gear which engages with a worm wheel on another spindle carrying a cam; the cam follower is attached to a pivoted pen-arm, and the pen is lifted up the chart, falling to its low position by gravity after passing the highest point of the cam. The downward movement is slowed by an air dash-pot. There is no new principle involved, and recorders of this general type have

been listed by meteorological-instrument makers for many years. Such a recorder can be used to record any quantity which can be transmitted in the form of electrical impulses.

The requirements for this particular recorder were :

(i) It should work with a standard (Mk 4) cup-contact anemometer.

(ii) If possible, it should be able to work with a Type 4 sensitive anemometer; but this was not proceeded with.

(iii) It should have some range adjustment, giving 50, 100 or 200 statute miles as full-scale deflexion.

(iv) It should use a standard Meteorological Office weekly clock and drum, and make use of an existing chart (Barograph Form 4237) on which 10 mb would represent 5, 10 or 20 miles, the pen arm being of the same length as the barograph pen appropriate to the chart.

(v) It should work on 6 volts d.c.

Calculation of gear ratios and impulse wheel teeth. In the Mk 4 cup-contact anemometer, each contact represents 49 cup revolutions; and a speed of 50 knots gives 490 rev/min or 10 contacts/minute. So 50×6080 feet are represented by 10×60 contacts from which it can be shown that 50 statute miles $= 50 \times 5280$ feet $= 522$ contacts.

The cam must therefore raise the pen in 522 contacts for 50 miles, 1044 for 100 miles, and 2088 for 200 miles. Since $522 = 29 \times 18$, the impulse wheel has 29 teeth, and drives the cam spindle through an 18 : 1 worm reduction gear.

For 100 and 200 miles, the worm ratios are 36 : 1 and 72 : 1 respectively. These three choices of ratio are obtained by having three different worm wheels each with 72 teeth, and three worm gears of 1, 2 and 4 starts, the worm-wheel teeth being cut at angles appropriate to the worms of 1, 2 and 4 starts. This arrangement gives the same centre distance between worm and worm wheel for the three ratios.

Worms and worm wheels are fixed to their spindles by grub screws; when the desired range has been selected and its gears fixed to their spindles, the other two pairs are 'parked' out of the way on the spindles on either side of the gears in use. The gears are colour-coded for easy selection.

The recorder is illustrated in Plates I to III.

Plate I — Shows the recorder complete with cover.

Plate II — Shows the recorder with the cover removed; the 29-tooth impulse wheel can be seen to the right of the clock drum, with the solenoid below it; the glass pen and reservoir are shown at the end of the pen arm, and the slots in the pen arm hold the cross-bar which lifts the plunger of the air dash-pot.

Plate III — Shows the worms and worm wheels; 18 : 1 gears are engaged.

Acknowledgement. The instruments were made in the workshop of the Operational Instrumentation Branch of the Meteorological Office at Bracknell, and the author acknowledges with thanks various design suggestions and excellent workmanship from the head of workshop and the craftsmen concerned.

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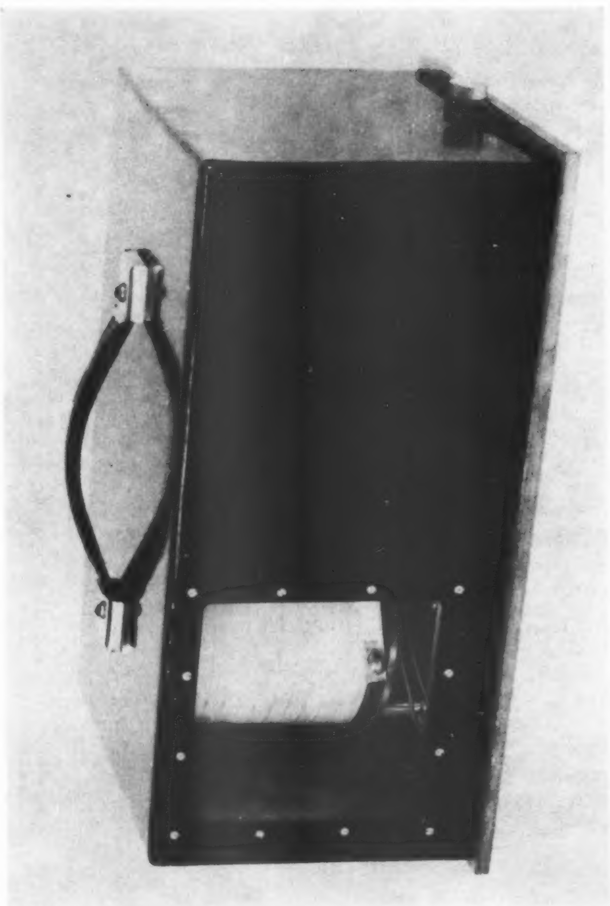

PLATE I—RUN-OF-WIND RECORDER, COMPLETE WITH COVER

See page 208.

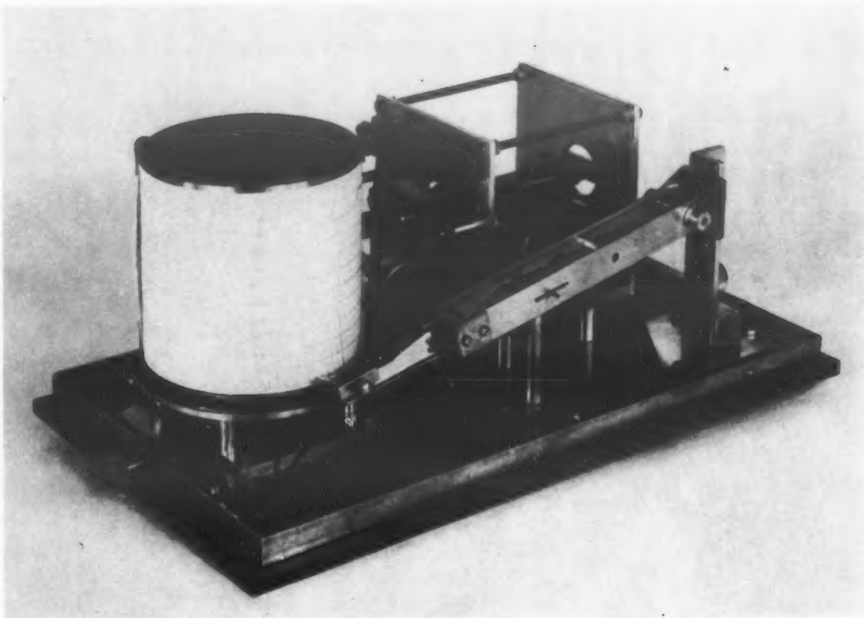

PLATE II—RUN-OF-WIND RECORDER WITH COVER REMOVED

See page 208.

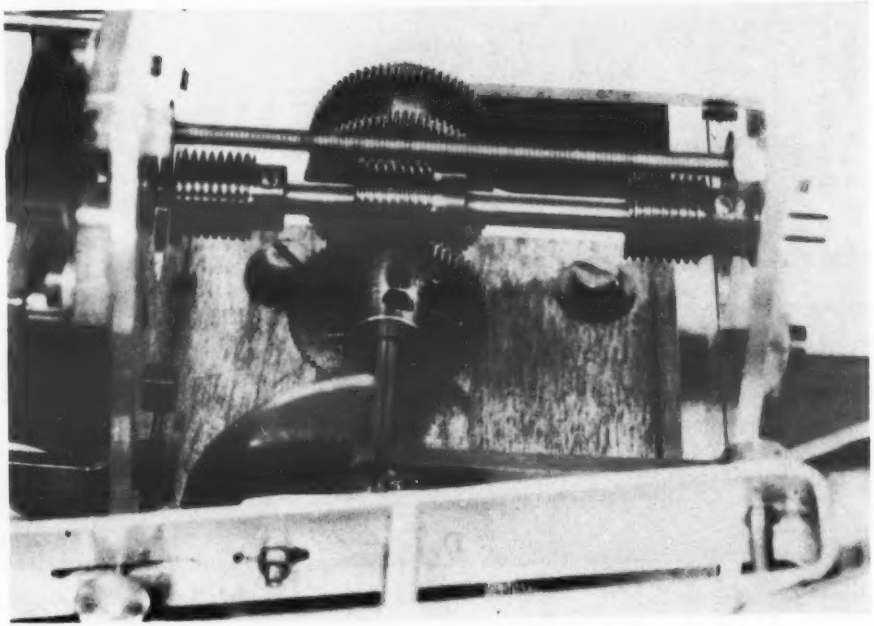

PLATE III—RUN-OF-WIND RECORDER SHOWING WORMS AND WORM WHEEL

See page 208.

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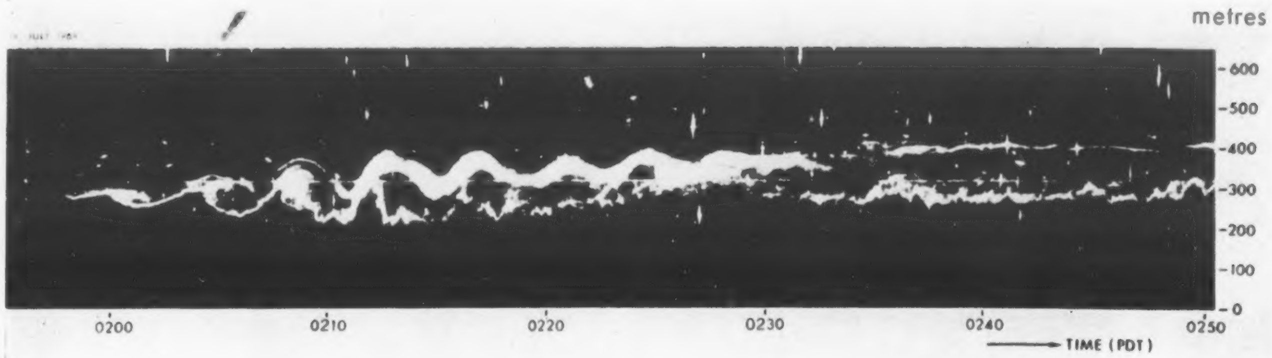

PLATE IV—TIME–HEIGHT RECORD OF WAVES AND TURBULENCE FORM RADAR DISPLAY ON 19 JULY 1969, WITH 2-m VERTICAL RESOLUTION (after Atlas *et alii*[11])

Unstable waves and subsequent turbulence in lower layer contrast with smooth structure of the upper layer. The double layer structure observed after 0230 is characteristic of many clear-air echoes. (See page 216)

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GRAVITY WAVE SEVERE TURBULENCE NEAR CYPRUS

By R. N. HARDY

Summary. On several occasions in recent years aircraft have encountered severe low-level turbulence near Cyprus which could not have been induced by topography or convection. Some case histories are summarized, a possible cause discussed and forecasting rules suggested.

Some case histories. Table I summarizes the six occasions of turbulence considered here. If g is the acceleration due to gravity then $\pm\frac{1}{2}g$ is generally accepted as marking the threshold of severe turbulence and it is clear from the table that in some cases pilot reports and accelerometer readings indicate extremely severe turbulence. It is also worthy of note that all the cases occurred in the period February to April.

1. *21 March 1962 near Derna (see Figure 1).* The first tabulated occasion was reported by Grimmer[1] and analysed by Kirk;[2] only the main synoptic features are summarized here.

(i) The nearest radiosonde ascent, Tobruk (see Figure 1) for 12 GMT 21 March, was very dry and showed a narrow inversion near 900 mb with near dry adiabatic layers above and below.

(ii) There was a strong low-level southerly flow and a trough associated with a deepening low over north-west Tunisia was moving towards the area.

(iii) Winds decreased and veered with height above 900 mb.

(iv) All nearby barograms showed jumps and oscillations.

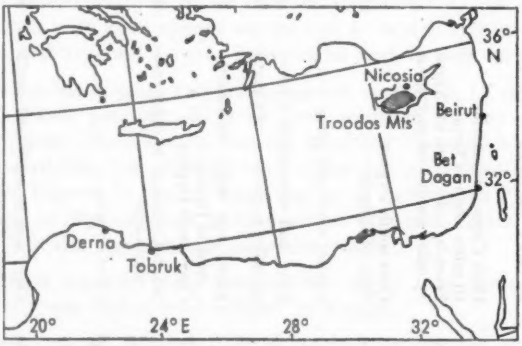

FIGURE 1—EASTERN MEDITERRANEAN

2. *14 April 1966 south of Cyprus.* This case was recorded in detail by Jefferson[3] and the similarities with the Derna case did not go unremarked. Here, however, not only was the turbulence very severe, but it persisted for about 18 hours and extended to nearly 24 000 feet.* Features noted were as follows :

(i) Both the Nicosia ascents during the period of turbulence showed a deep layer with near dry-adiabatic lapse rate (DALR) and an intense low-level inversion.

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* Distances and heights are given in traditional British units. Conversion factors to metric units are : 1 foot = 0·3048 m; 1 mile = 1·6 km; 1 knot ≈ 0·5 m/s.

TABLE I—OCCASIONS OF SEVERE LOW-LEVEL TURBULENCE IN THE EASTERN MEDITERRANEAN

	Date	Time(s) GMT	Approximate location	Height(s) *feet*	Intensity of turbulence	Cloud
1.	21 Mar. 1962	0600	25 miles north-east of Derna	4500	'More severe than cumulonimbus'	Clear
2.	14 Apr. 1966	1300	Over Cyprus mountains	14 000 and below	Severe	Not reported
		1600	10 miles south of Cyprus	4000 to 16 000	$+3$ to $-1\frac{1}{2}$ g*	Not reported
		circa 1610	From 80 miles south to Cyprus	1000	Severe	Not reported
		1730	25 miles south-west of Cyprus	8500	$+7$ to -3 g	8/8 medium, good breaks overnight
		1940	Over south Cyprus	7500	Moderate to severe	Not reported
	15 Apr. 1966	*circa* 0300	West of Cyprus	Descending from 24 000	Occasional, moderate	In layered cloud
3.	18 Feb. 1968	1110	2 miles south of Cyprus	1500	$\pm 1\frac{1}{2}$ g, 'very sudden concentrated bumps'	8/8 medium
		1200	Over and near south Cyprus	1500 to 10 000	Severe	Not reported
4.	28 Feb. 1968	1530	50 miles south-west of Cyprus	7000 to 12 000	Moderate to severe	Mostly 7/8 medium and high
			From 150 miles west-south-west to Cyprus	33 000 to 28 000 and 12 000 to 3000	Moderate, locally severe	Not reported
	29 Feb. 1968	0820	Over south Cyprus	1000 to 4000	Up to 2 g	Not reported
5.	12 Mar. 1968	0830	South Cyprus to 25 miles east-south-east	Surface to unspecified height	± 1 g	6–8/8 medium with thick dust haze beneath
		0915–1030	Over Cyprus	1000 to 9000	Moderate to severe, 'some rapid altitude variations of about 500 ft/min'	Not reported
6.	17 Feb. 1969	0330–1200 (approx.)	Over and to south and south-east of Cyprus	2000 to 20 000	Moderate, occasionally severe	Generally large amounts of medium cloud
				7000	Moderate to severe	
				{ 6000 to 12 000	Severe	
				{ 12 000 to 18 000	Moderate to severe	
				3000 to 7000	Severe	

* g = acceleration due to gravity

(ii) Barograms from stations on the southern coast of Cyprus showed short-period oscillations of up to 3 mb.

(iii) Winds were strong at low levels and veered rapidly with height.

(iv) A strong 850-mb warm ridge preceded an eastward-moving trough.

(v) A depression was centred over Greece with an associated cold front accelerating towards Cyprus.

(vi) There was a complete cover of medium cloud throughout the period.

Jefferson suggested that in view of the similarity with Case 1 near Derna, factors (i) to (iv) may be useful parameters for forecasting future occurrences and, with minor refinements, this has been done successfully.

3. *18 February 1968 over and south of Cyprus.* Reports of turbulence on this occasion covered a period of only one hour but one aircraft experienced almost continuous severe clear-air turbulence (CAT) whilst descending from 10 000 to 1500 ft, clearly a potentially dangerous event.

The period 16–18 February 1968 was one of cyclogenesis over Greece with a deepening low moving north-east and an intensifying cold front accelerating eastwards. Figure 2 shows the 12 GMT surface analysis with 1000–500-mb thickness pattern superimposed for 16, 17 and 18 February; note particularly the increasing thermal gradient across the front. Simultaneously, anticyclogenesis took place over north Iraq producing an easterly component in the flow across the extreme north-east Mediterranean.

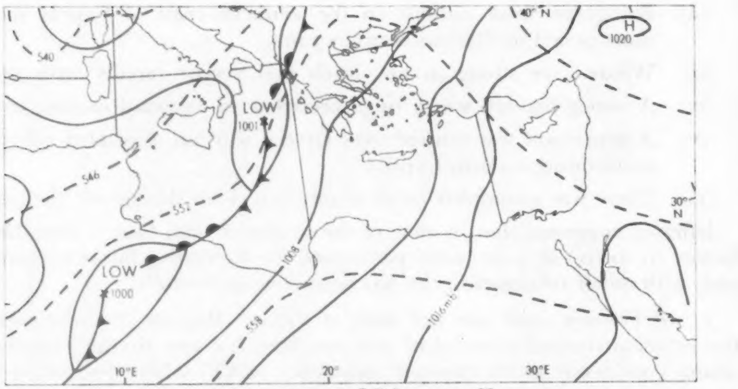
The development of the surface low can be related to a sharpening upper trough which moved to 19°E by 00 GMT on 18 February, and an associated jet near 300 mb with core speeds up to 140 kt which moved through the upper pattern and reached Cyprus between 06 and 12 GMT on 18 February.

Figure 3 shows the Nicosia radiosonde ascent curves for 12 GMT on 17 and 18 February. These profiles will have been modified by any waves in the atmosphere because Nicosia is to the north of the Troodos Mountains (see Figure 1); nevertheless the profiles clearly show that a layer with near DALR developed over Cyprus in the 24 hours up to 12 GMT on 18 February, with strong warming at 850 mb and cooling above 800 mb. Thick cloud above about 12 000 ft is also apparent ahead of the cold air.

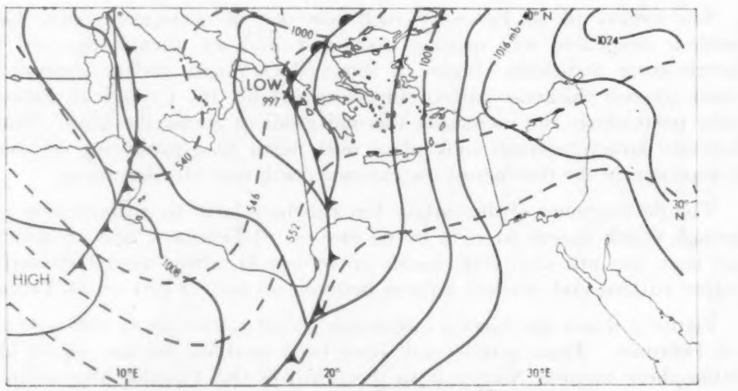
Cyprus stations reported only intermittent slight rain from 11 GMT but thundery activity was widespread behind the trough.

The cold front passed through Tobruk during the evening of 17 February preceded by 8/8 altocumulus and altostratus accompanied by blowing sand in strong southerly winds. The Tobruk radiosonde ascent for 12 GMT on 17 February in Figure 4 is very similar to the Nicosia profile at 00 GMT on 14 April 1966[3] (Case 2) and the 06 GMT winds (Table II) compare closely with those on 20 March 1962[2] (Case 1), particularly as regards the strong shear at low levels.

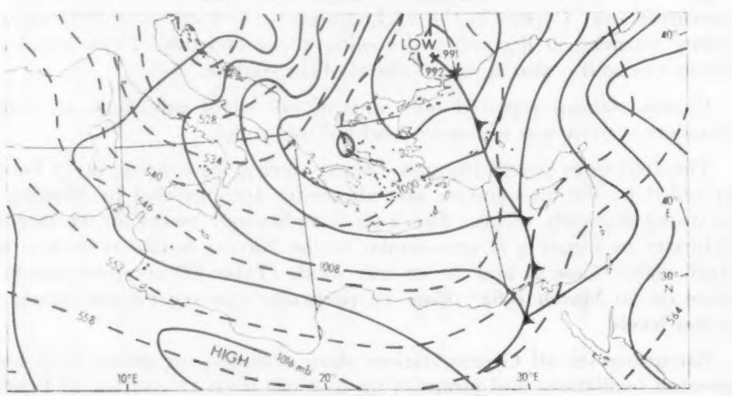
Barograms for all Cyprus stations show a three-hour period with marked pressure oscillations and jumps of up to 2 mb from 11 GMT on 18 February; the disturbances were less marked at Nicosia to the lee of the main mountain range. The Tobruk pressure record shows disturbances from 17 GMT on 17 February for about six hours though the amplitude of the oscillations appears



(a) 12 GMT on 16 February 1968



(b) 12 GMT on 17 February 1968



(c) 12 GMT on 18 February 1968

FIGURE 2—SURFACE ANALYSIS AND 1000–500-mb THICKNESS

——— Isobars — — — Thickness in geopotential decametres

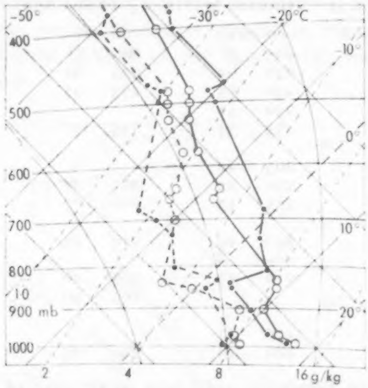


FIGURE 3—NICOSIA ASCENTS, 17 AND 18 FEBRUARY 1968

17 February	18 February
· —— · Temperature	o —— o Temperature
· – – – · Dew-point	o – – – o Dew-point

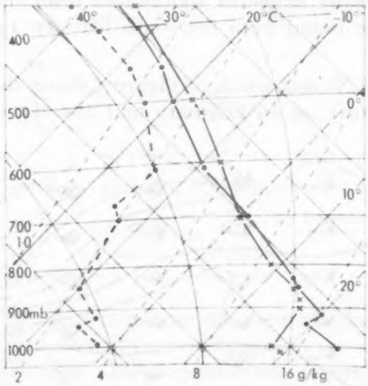


FIGURE 4—TOBRUK ASCENTS, 00 AND 12 GMT ON 17 FEBRUARY 1968

00 GMT	12 GMT
· —— · Temperature	x —— x Temperature
· – – – · Dew-point	

to be less than at Cyprus stations; this may reflect differences between the instruments concerned. Barograms for Beirut and Beit Degan (see Figure 1) showed some trace of pre-frontal oscillations but not to the same degree as those recorded by Cyprus stations.

4. *28 and 29 February 1968 near Cyprus.* The duration and area of turbulence reported on this occasion more nearly corresponds to that of Case 2. Severe turbulence was encountered from 1000 ft to the base of a nearly complete cover of medium cloud at 12 000 ft and in addition moderate, locally severe, turbulence was reported from 28 000 to 33 000 ft associated with a high-level jet stream.

TABLE II—TOBRUK WINDS 17 FEBRUARY 1968

Pressure level	00 GMT		06 GMT		12 GMT	
mb	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*
300	240	64	235	61	230	47
400	240	55	235	47	235	41
485	230	51				
500	235	54	235	42	225	36
524					225	30
592	205	22				
600	210	22	255	22	220	28
700	235	15	220	07	220	29
764					225	32
800	230	19	210	25	223	34
829	220	18				
850	210	17	205	28	220	34
900			185	40	211	36
963					205	32
970	170	37				
1000	180	18	190	25	190	22

The period 27 to 29 February 1968 was again one of marked cyclogenesis west of Cyprus. A depression developed in an area of almost uniform pressure some 300 miles west of Tobruk; from a central pressure of 1004 mb at 06 GMT on 28 February the low deepened to 981 mb at 12 GMT on 29 February having moved north-eastwards to a position 300 miles west of Cyprus. An associated cold front that originally extended southwards from the centre accelerated markedly to cross the island from the south between 12 and 18 GMT on 29 February.

The time section of Nicosia winds in Figure 5 shows the increasing shear at low levels up to 12 GMT on 29 February and also the strong high-level jet.

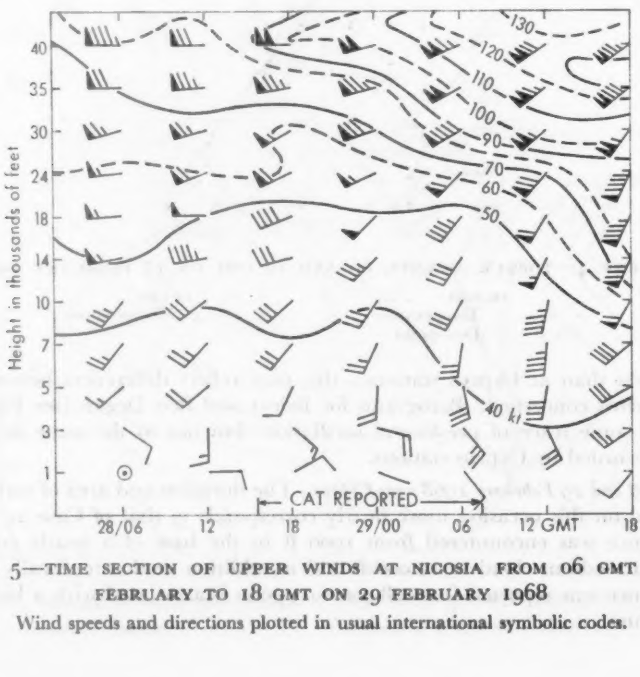


FIGURE 5—TIME SECTION OF UPPER WINDS AT NICOSIA FROM 06 GMT ON 28 FEBRUARY TO 18 GMT ON 29 FEBRUARY 1968

Wind speeds and directions plotted in usual international symbolic codes.

Figure 6 shows the Nicosia radiosonde ascents for 28 and 29 February; again the marked low-level warm advection gradually became established and extended a layer of near DALR at the same time modifying more stable layers above and below.

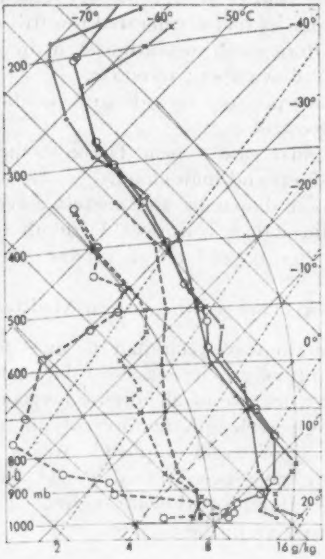


FIGURE 6—NICOSIA ASCENTS, 28 AND 29 FEBRUARY 1968

28 February	29 February	
12 GMT	00 GMT	12 GMT
· —— · Temperature	o —— o Temperature	x —— x Temperature
· - - - · Dew-point	o - - o Dew-point	x - - x Dew-point

Isolated outbreaks of slight rain from 8/8 medium cloud were reported on the south coast of Cyprus, but there were breaks in the cloud cover overnight between 28 and 29 February. Blowing sand was reported over North Africa on both sides of the front and dust haze was widespread over Cyprus on the 29th. Barograms show the typical unsettled traces of the previous occasions.

5. *12 March 1968 and 17 February 1969.* These occasions of severe turbulence near Cyprus were broadly similar to those already described but each contributed one significant item of additional information.

On 12 March 1968 a pilot described the turbulence as taking the form of 'some rapid altitude variations of about 500 ft/min', implying wave motion.

On 17 February 1969 there was no marked surface trough associated with the area of turbulence. In this case an intensifying 850-mb trough with associated strong baroclinic zone accelerated towards Cyprus and became associated with a developing surface low south-south-west of the island.

Discussion.

Common factors. The synoptic patterns and sequences of events leading to the six occasions of severe low-level turbulence were very much alike.

Common factors were :

(i) All occasions were in the period February to April.

(ii) Warm dry air was being advected at low levels by a strong south to south-east flow.

(iii) An intensifying front or trough usually associated with a surface low and strong upper jet had accelerated towards the area.

(iv) Winds veered from south to south-east at the surface to between west and south-west above about 10 000 ft.

(v) Unsteady surface pressure records with oscillations and jumps were a feature of each occasion.

(vi) Except in the first case — near Derna — there was always a large amount of medium and high cloud.

(vii) The stratification shown by the nearest ascent invariably showed a near DALR through a considerable depth of the low troposphere. Over the sea there would be an intense low-level inversion or isothermal layer.

(viii) All known reports concern the eastern Mediterranean.

Gravity waves. Mountain waves, familiar to most forecasters, are just one member of a wider family of gravity waves in the atmosphere. It is probable that gravity waves are a feature of all intense inversions though mostly they are low-amplitude long-wavelength features of no operational importance. Occasions are on record of larger-amplitude waves propagating over long distances whose origins have been traced to (i) cyclogenesis,[4] (ii) intense convection[5] and (iii) evaporation downdraughts.[6] Factors (i) and perhaps (iii) may have been operative in these cases.

It is possible that waves travelling along an inversion which is becoming shallower but more intense can amplify and disrupt, giving areas of severe turbulence. Amplifying gravity waves could be the cause of the pressure and wind oscillations that have been noted in the Mediterranean[7] and Persian Gulf.[8] If the 'broken' wave differs in character from the oscillatory wave in the same way as a sea wave, turbulent zones may travel along the hitherto undisturbed inversion downstream to produce discrete pressure jumps.

Kelvin-Helmholtz instability (KHI). KHI does not belong to the gravity-wave family but is a form of dynamic instability produced by strong vertical shear in stably stratified fluids. It takes the form of wave-like disturbances in which the crests grow and roll up into horizontal vortices (billows) which then 'burst' into general turbulence after a short time (less than one minute). Photographs of KHI development in the ocean thermocline have been taken by Woods[9] and more recently, radar pictures of what appears to be atmospheric KHI have been obtained.[10,11] (See Plate IV.)

It has been shown (see for example the discussion of billow clouds by Ludlam[12]) that this 'liberation' of kinetic energy from shear layers can only occur if the Richardson number, *(Ri)*, is less than some critical value about 0·25 where, over a layer of thickness Δz,

$$(Ri) = \frac{g}{\theta} \quad \frac{\Delta\theta}{\Delta V} \quad \frac{\Delta z}{\Delta V},$$

where θ = potential temperature, g = acceleration due to gravity and $\Delta\theta$ and ΔV are the differences of potential temperature and wind velocity over the layer.

Normally it appears that *(Ri)* is reduced to its critical value in very narrow zones across which direct measurements of the shear and potential temperature gradient are not practicable. Computations of *(Ri)* from radiosonde ascents do however give a useful guide since the layer *(Ri)* is always greater than the true *(Ri)* at some point in that layer. In other words if *(Ri)* computed over a layer of say 1 km approaches 0·25 then it is almost certain to be less than the critical value over part of the layer.

By calculating values of *(Ri)* for the occasions of severe low-level turbulence described in the case histories and comparing the profiles with those occasions when KHI was detected by radar, it should be possible to assess the likelihood of KHI and the probable depth of atmosphere affected. Unfortunately the lack of representative data prevents a detailed analysis; in particular Nicosia radiosonde ascents cannot be used since Nicosia lies to the lee of a mountain range. Tobruk radiosonde ascent and winds for 17 February 1968 shown in Figure 4 and Table II respectively are considered broadly representative of the type of profile on all occasions of turbulence except that the lowest layers would be much more stable over the sea. Suitably modified *(Ri)* profiles are shown in Figure 7 with the shear and gradient of potential temperature also given separately. There is some evidence that KHI could have occurred in the layer 850–800 mb near 00 GMT, because not only is *(Ri)* well below 0·25 but the 06 GMT profile shows a reduction of *(Ri)* above and below this layer with a marked increase in the layer itself, a feature which has been noted during radar investigations of KHI. A forecaster would be justified in predicting locally severe turbulence from the 06 GMT *(Ri)* profile where the critical value is almost certainly reached at some point between 900 and 850 mb. Furthermore, a relatively small increase in shear or decrease in stability would reduce *(Ri)* below the critical value at 12 GMT.

Caution should be used in interpreting *(Ri)* profiles. With a near DALR there is uncertainty as to the exact value of *(Ri)*, furthermore, it is known that dry adiabatic lapse rates (or even superadiabatic lapse rates) occur in the lower layers without leading to severe turbulence. Possibly the destabilization caused by overrunning colder air in a region of shear is of major significance. If it occurs above an inversion which isolates it from the small-scale turbulence near the ground then energy is dissipated in large-scale rather than small-scale eddies. Clearly it is the values of *(Ri)* in the shear layer that are most important.

The effect of gravity waves on the low-level inversion on *(Ri)* values may be critical; *(Ri)* will be reduced at the crests and troughs where shear is concentrated, triggering KHI where it would not otherwise have occurred.

The persistence of the turbulence on some of the occasions described is probably due to the generation of shear ahead of the frontal trough counter-balancing the dissipation due to KHI; this process is discussed in detail by Roach[13] elsewhere. It is likely that the vertical extent of turbulence is a function of stability above the KHI layer; in these cases the disturbances are allowed to propagate upwards virtually undamped through the layer of near DALR.

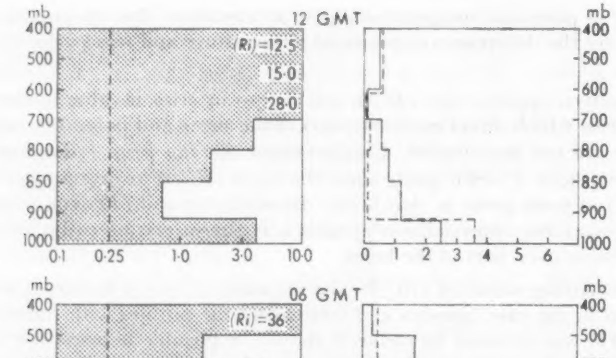


FIGURE 7—PROFILES OF RICHARDSON NUMBER, VERTICAL SHEAR AND GRADIENT OF POTENTIAL TEMPERATURE FOR TOBRUK ON 17 FEBRUARY 1968

V = Wind velocity θ = Potential temperature
Δz = Thickness of layer

General considerations. The severe CAT reported in the eastern Mediterranean occurred in regions where a particular intense form of KHI might be expected. It occurs when cyclogenesis to the west establishes a strong wind shear in the vertical which in turn, because of the geography of the area, means the establishment of a layer of near DALR in the lower troposphere. During the period January to April an intense low-level inversion is inevitable over the eastern Mediterranean in this situation, which tends to concentrate shear and forms a basis for wave motion.

KHI may be triggered by local minima of *(Ri)* produced by local distortion of shear layers by travelling gravity waves (e.g. Woods[9]) which themselves may be generated by downdraughts or the cyclogenesis itself. However, until more information becomes available the forecaster can only assume a random

distribution of turbulence in the horizontal within the zone of potential KHI. There is some evidence that the tendency of KHI to concentrate stability at the top and bottom of the layer of turbulence causes the turbulence to persist longest in these regions, see Plate IV, but the upper boundary of KHI (near Cyprus at least) is likely to be marked by the base of extensive medium cloud; the lower boundary may well be at the surface.

It may be possible to advise aircrew on occasions to fly in the medium cloud or if that is impossible then to fly midway between the likely bounds of KHI. Ideally, descent through or take-off into the layer would be delayed until after the passage of the surface front.

Forecasting rules. There are few difficulties in forecasting qualitatively the probable occurrence of this type of turbulence in the eastern Mediterranean or its likely vertical extent. The horizontal area is difficult to specify except in so far as the surface front marks the rear boundary.

The synoptic events leading to occasions of severe turbulence are almost identical to those preceding the devastating tornadoes of December 1969.[14] The most significant difference lies in the month of occurrence; it is probable that the higher sea temperatures of December and hence moister air ahead of the front led to the genesis of waterspouts rather than to KHI.

The conditions for turbulence of this type, all of which are interrelated, are as follows :

(i) A deepening depression to the west of the area.
(ii) An associated trough or cold front moving towards the area.
(iii) Strong low-level winds veering with height, giving warm advection at low levels and often accompanied by cold advection aloft.
(iv) A near DALR through a considerable depth of the lower troposphere with an inversion beneath.
(v) Unsteady barograph traces, often with discrete jumps.
(vi) Usually hazy conditions at low levels with a complete cover of medium cloud.
(vii) The preceding night minimum temperature is always well above normal.

Now that radiosonde ascents are made from Episkopi on the south coast of Cyprus it may be possible to investigate the profiles of *(Ri)* in more detail on future occasions. A great deal more could be learnt by using high-power radar; it appears that the eastern Mediterranean would be a most suitable area for such research.

Acknowledgement. The author is indebted to Dr W. T. Roach for useful discussions on the nature of KHI.

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551.524.36

THE ESTIMATION OF MEAN DRY-BULB TEMPERATURE DURING DAYLIGHT HOURS

By D. G. ARMOUR, J. BALLOCH and R. W. GLOYNE

Summary. Botanists state that the mean temperature during the hours of daylight is a useful parameter for studying phenological data. Relatively few stations make observations of temperature at each hour; many, however, record the daily maximum and minimum. Empirical expressions have been derived for obtaining an estimate of mean temperature during the day by subtracting from the average of daily maxima a proportion of the average daily range. Values for the constant of proportionality are presented. These vary from about 0·25 for California (with little or no seasonal variation) to rather higher absolute values (exhibiting a seasonal variation) of between 0·32 and 0·46 for selected stations in England and Scotland.

Introduction. The mean temperature during the hours of daylight (and equally during the hours of darkness) has been found to be a useful concept for organizing and analysing certain phenological data. A request for mean day-time temperature by months for several places provided the opportunity to examine formulae for deriving this parameter from readily available data on average mean daily maximum and average mean daily minimum temperatures for individual months.

Average monthly values of hour-by-hour dry-bulb temperatures for the period 1957–66 were readily available for Edinburgh (Edinburgh/Turnhouse Airport) and London (London/Heathrow Airport) and these, together with estimates (based on observations for each three hours) for Paris (St Maur)[1] for the period 1951–60, form the basic material for the computations.

Method and analysis.

(i) *Data.*

London : Mean hourly dry-bulb temperatures (month-by-month) for 1957 to 1966 (Metform 3257).
Average daily maximum and minimum temperatures for 1957 to 1966 (Metform 3259).

Edinburgh : Mean hourly dry-bulb temperatures (month-by-month) for 1957 to 1966 (Metform 3257).
Average daily maximum and minimum temperatures for 1957 to 1966 (Metform 3259).

Paris : Estimates of mean hourly dry-bulb temperatures based on 3-hourly observations for 1951 to 1960.[1]
Average daily maximum and minimum temperatures.[2]
Day lengths for the 15th day of each month were taken from the Nautical Almanac.[3]

(ii) *Procedures.* The method consists of subtracting a proportion of the mean daily range from the mean daily maximum — average values of these quantities having been derived for months of given name, i.e. the expression is of the form

$$T = X - a\,(X - N),$$

where

T = average value of the mean temperature during daylight hours,
X = average value of daily maximum temperature,
N = average value of daily minimum temperature,
a = a coefficient to be determined from the data.

A mean temperature quoted for a particular hour (hh) was regarded as the mean value for the period (hh−30 min) to (hh+30 min). Temperatures for incomplete 60 minutes at sunrise and sunset were weighted according to the convention :

$\leqslant$15 min :	0 × hourly value
16 to 45 min :	½ × hourly value
>45 min :	1 × hourly value

Values for the coefficient a were computed from

$$a = (X - T)/(X - N).$$

The magnitude of a was noted to be rather sensitive to decisions as to the weightings to be attributed to incomplete hours. Accordingly the simple graduation formula was employed, viz,

$$a = \tfrac{1}{4}(a_{n-1} + 2a_n + a_{n+1}),$$

where a_{n-1}, a_n, a_{n+1} are the computed values for successive months, and a is the 'smoothed' mean value for month n (Conrad[4]).

(iii) *Results.* The values for London, Edinburgh and Paris are set out in Table I, together with those derived by Brooks[5] for California and Smith[6] for Aberdeen and Kew.

TABLE I—PROPORTION OF MEAN DAILY RANGE TO BE SUBTRACTED FROM MEAN DAILY MAXIMUM TO OBTAIN A MEAN DAY-TIME TEMPERATURE

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Edinburgh (Turnhouse)	0·34	0·35	0·38	0·39	0·41	0·45	0·42	0·40	0·37	0·35	0·36	0·34
London (Heathrow)	0·36	0·39	0·39	0·40	0·42	0·46	0·43	0·41	0·42	0·36	0·39	0·32
Kew (from Smith[6])	0·33	0·34	0·35	0·35	0·37	0·41	0·39	0·39	0·35	0·33	0·32	0·30
Aberdeen (from Smith[6])	0·35	0·35	0·34	0·36	0·39	0·43	0·40	0·39	0·35	0·29	0·30	0·36
Paris (St Maur)	0·31	0·39	0·38	0·37	0·37	0·39	0·41	0·40	0·37	0·35	0·30	0·24
California (from Brooks[5])	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25

Clearly there are two groups representing respectively the results for the British Isles and those for France (Paris) on the one hand and the U.S.A. (California) on the other. In this second group the factors show little or no

seasonal variation about an average of 0·25; in the first absolute values are higher and there is a seasonal maximum in summer.

It was noted that the unsmoothed monthly values for the British Isles followed a more irregular sequence after, as compared with before, the summer peak.

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REVIEW

Measurement of humidity, Notes on Applied Science No. 4, fourth edition, by M. J. Hickman. 243 mm × 150 mm, pp. v+33, *illus.*, HMSO, 49 High Holborn, London WC1, 1970. Price: 20p.

This is one of the excellent series of booklets on applied physical topics issued by the National Physical Laboratory. It is an introduction to practical methods of humidity measurement as required in industry and laboratories and brings the previous editions up to date. As Mr Hickman explains, the notes make no pretension to detail or completeness and are meant for the non-specialist. Those interested in the measurement of humidity in the open air for meteorological purposes are referred to books issued by the Meteorological Office.

The booklet starts with a brief description of physical principles and continues with an outline of the main types of hygrometer likely to be useful in solving practical problems — the wet- and dry-bulb hygrometer, dew-point hygrometer, mechanical hygrometer and electrical hygrometer — with a brief mention of some miscellaneous types.

The wet- and dry-bulb hygrometer is undoubtedly one of the most convenient instruments for obtaining quite accurate measurements so, quite rightly, more detail is given of this type of hygrometer than any other together with a fairly comprehensive list of sources of error.

The section on dew-point hygrometers makes little mention of completely automatic types and the statement is made that such instruments are complicated and expensive. However, the manually operated types of dew-point hygrometer require a skilled operator while the automatic types do not. A wide variety of automatic instruments is now becoming available, some of which are not unduly expensive. They further have the advantage of potentially remote operation and relatively high accuracy as well as automatic indication.

After a description of mechanical hygrometers and of hygrometers which can be used for low humidities, there is a section on the need for operators

to check their instruments frequently, something which is not always done as much as it should be, as the accuracy of most hygrometers is subject to deteriorating influences. A further section gives guidance on the choice of methods to be considered especially in relation to the accuracy required. Finally there are a few concluding remarks about methods of generating air-streams of known humidity.

A comprehensive reference section at the end of the booklet makes it a useful introduction for the intending specialist too; nevertheless the references are laid out so that the non-specialist can easily pick out those few papers which he is likely to wish to study.

This is a booklet which all who have any connection with humidity problems ought to have on their bookshelves.

C. K. FOLLAND

LETTER TO THE EDITOR

551.578.45:625.1

A railway problem during the heavy snowfall of 4 March 1970

It is regretted that the series of observations for Cardington and Northolt given in Table I of the above article* should be from 06 to 15 GMT and not 07 to 16 GMT. Also, Cardington is not closed overnight; gaps appear in the Table because the data were not relevant to the argument. The text on page 300 should now read '... at Cardington and Northolt between 10 and 12 GMT' and on page 303 '... at Northolt between 09 and 12 before snow returned by 13 GMT', but the general argument of the article is not altered.

It should be pointed out however, that the latent heat released by the freezing of rain on a sub-zero pantograph would quickly raise the temperature, and accretion by this process is limited.

Dr Bartlett has made some estimates of the time required for a pantograph temperature of −2°C to become 0°C. He has assumed that the pantograph is constructed of bars which are the equivalent of solid steel bars about 1 inch (2·54 cm) diameter, though the construction is somewhat lighter than this, with an approximate specific heat 0·1 and density 7·9 g/cm^3. The pantographs normally exert an upward thrust equivalent to a weight of 20 lb (about 10 kg).

(i) *For a dry pantograph.* At a relative airspeed of 30 mile/h (15 m/s) with an environment temperature of 0°C the pantograph temperature would rise to 0°C in 6 to 10 minutes, i.e. over a distance of 3 to 5 miles.

(ii) *Under wet conditions.* At a relative airspeed of 60 mile/h (30 m/s) with the equivalent of slight rain (0·5 mm/h on the ground) the pantograph temperature would rise to 0°C in about 6 minutes.

In moderate to heavy snow the weight accumulated on a pantograph with a surface area of about 1 square metre would be about 10 kg/m^2 in 6 minutes at a relative airspeed of 60 mile/h (30 m/s), i.e. over a distance of about 6 miles.

* PARREY, G. E.; A railway problem during the heavy snowfall of 4 March 1970. *Met Mag, London,* **99**, 1970, pp. 299–304.

Slight rain (equivalent to 0·5 mm/h on the ground) mixed with the snow is assumed to freeze on the pantograph and result in all the precipitation sticking to the pantograph.

It will be seen from these figures that a cold pantograph very quickly reaches 0°C and that rather special conditions are required before water drops could freeze on a cold pantograph and lead to a weight of snow and ice sufficient to lower the pantograph. The air-temperature change from -2°C to 0°C would need to occur within about 5 miles and the amount of water actually freezing would need to be minimal; most of the weight accumulating would be of snow.

Meteorological Office, Watnall G. E. PARREY

OBITUARY

It is with regret we record the death of Mr R. A. Smith, Senior Scientific Assistant, Birmingham Airport, on 3 March 1971.

PUBLICATION RECEIVED

Vayu Mandal (literally the Atmosphere) is the official Bulletin of the Indian Meteorological Society and will be published quarterly. Its annual subscription is Rs. 8 in India and $2·00 abroad. Vol. 1 No. 1 for January 1971 has now appeared, with a wide variety of articles on meteorology.

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